$W+$ jets and heavy flavour production

All-D0 meeting, July 23rd 2004

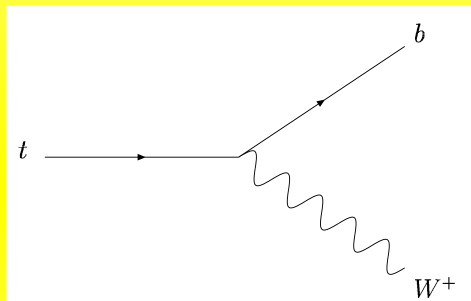
John Campbell
Argonne National Laboratory

Outline

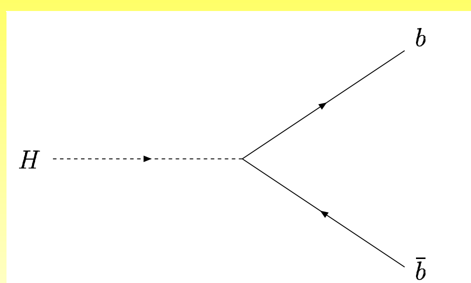
- The MCFM Monte Carlo
  - overview of the program
  - implementation of vector boson + jets processes
- NLO predictions for $W+2$ jets and $Wb\bar{b}$
  - basic cross-sections
  - theoretical similarities between the two processes
  - effect of NLO on distributions
- Single-tagged events
- Summary

Heavy flavour as a background

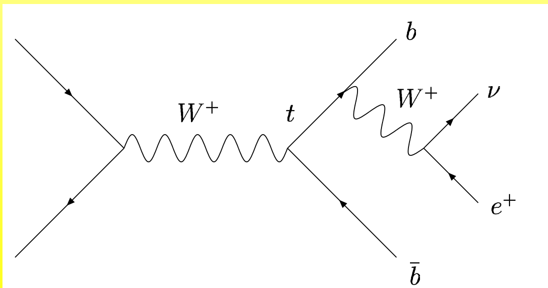
- Events containing jets that are heavy-quark tagged are important for understanding both old and new physics:
  - ⋆ Top decays $t \to W + b$



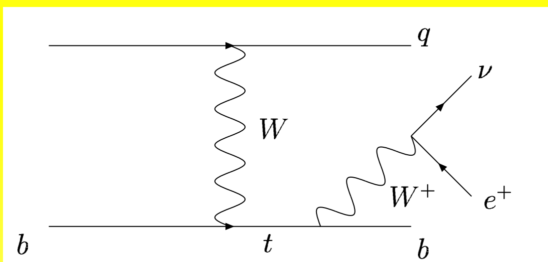
  - ⋆ Much new physics couples preferentially to massive quarks, for instance a light Higgs with $m_H < 140$ GeV decaying to $b\bar{b}$



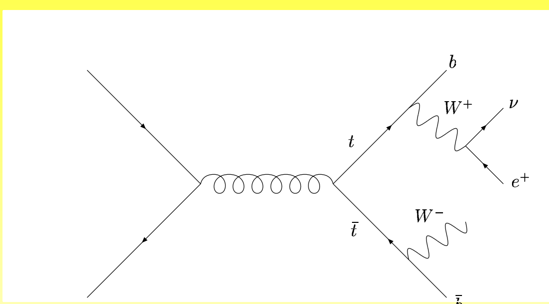
Top processes



$\longrightarrow$ 2 jets, both b's



$\longrightarrow$ 2 jets, only one is a b



$\longrightarrow$ ≥ 2 jets, two are b's

Overview of MCFM

MCFM overview

JC and R.K. Ellis

- Parton level cross-sections predicted to NLO in α_S

$p\bar{p} \to W^\pm/Z$	$p\bar{p} \to W^+ + W^-$
$p\bar{p} \to W^\pm + Z$	$p\bar{p} \to Z + Z$
$p\bar{p} \to W^\pm + \gamma$	$p\bar{p} \to W^\pm/Z + H$
$p\bar{p} \to W^\pm + g^\star\,(\to b\bar{b})$	$p\bar{p} \to Zb\bar{b}$
$p\bar{p} \to W^\pm/Z +$ 1 jet	$p\bar{p} \to W^\pm/Z +$ 2 jets
$p\bar{p}(gg) \to H$	$p\bar{p}(gg) \to H +$ 1 jet
$p\bar{p}(VV) \to H +$ 2 jets	

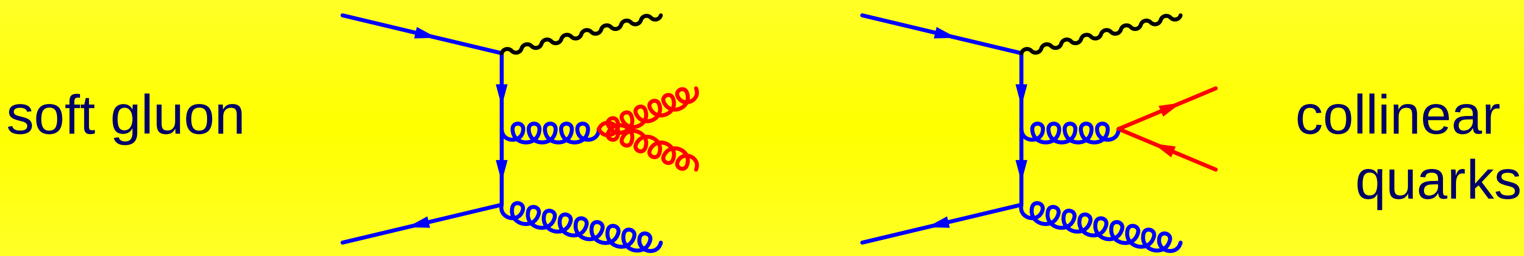
- $\ominus$ low particle multiplicity (no showering)
- $\ominus$ no hadronization
- $\ominus$ hard to model detector effects
- $\oplus$ less sensitivity to μ_R, μ_F
- $\oplus$ rates are better normalized
- $\oplus$ fully differential distributions

MCFM Information

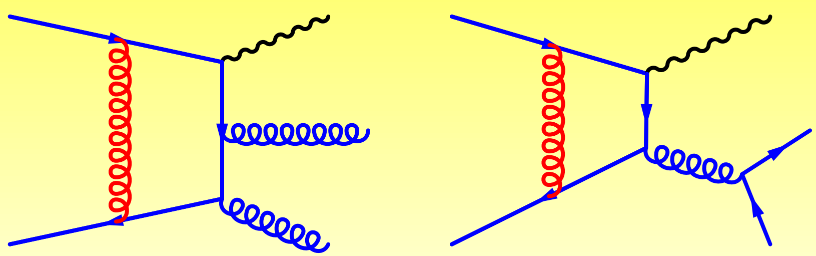
- Version 3.4.5 available at:
  `http://mcfm.fnal.gov`
- Improvements over previous releases:
  - ⋆ more processes
  - ⋆ better user interface
  - ⋆ support for PDFLIB, Les Houches PDF accord
    ($\longrightarrow$ PDF uncertainties)
  - ⋆ ntuples as well as histograms
  - ⋆ unweighted events
  - ⋆ Pythia/Les Houches generator interface (LO)
  - ⋆ 'Behind-the-scenes' efficiency
- Coming attractions:
  - ⋆ more processes ($Z + b$, single top, $\ldots$)
  - ⋆ separate variation of factorization and renormalization scales

Vector boson + jets in MCFM

- Many diagrams, sensitive to all parton PDF's
- NLO corrections are separated into two classes:
- REAL extra parton radiation, e.g. ($W/Z + 2$ jets)

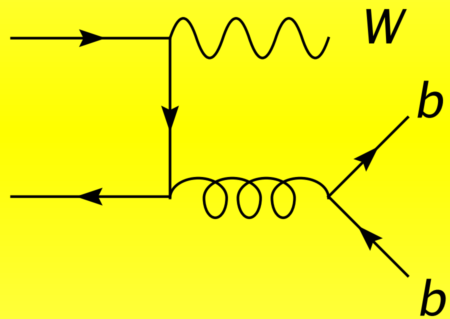


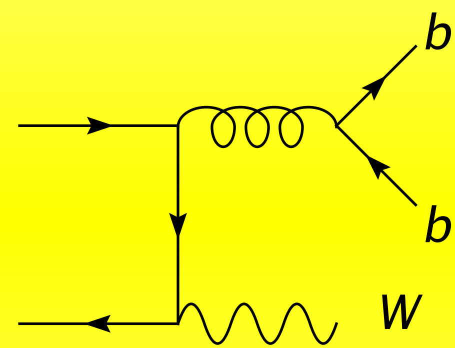
- VIRTUAL loop diagrams:



Vector boson + heavy flavour in MCFM

- In lowest order b-quark pairs are produced in association with W's by gluon splitting alone:

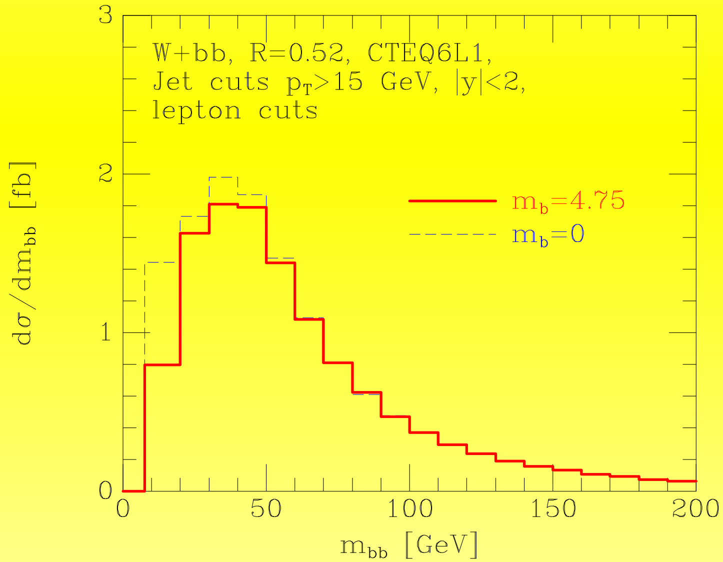


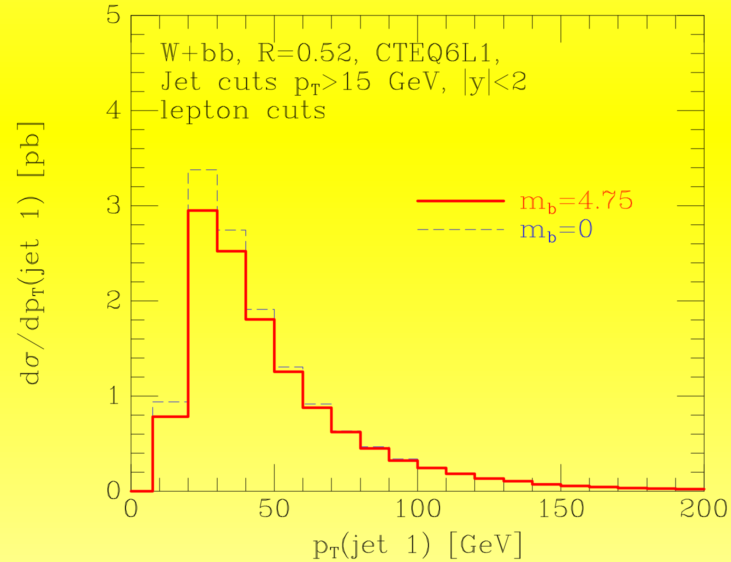


- Beyond LO, the b-quark is treated as a massless particle in MCFM
  - ⋆ a finite cross-section requires a cut on the b-quark p_T
  - ⋆ this means that this calculation is not suitable for estimating the rate with only a single b tag

Mass effects

- Lowest order comparison of dijet mass and leading jet p_T distributions for $Wb\bar{b}$
  - $\star$ $m_b = 4.75$ GeV (lowest order only)
  - $\star$ $m_b = 0$ (can be calculated to NLO)

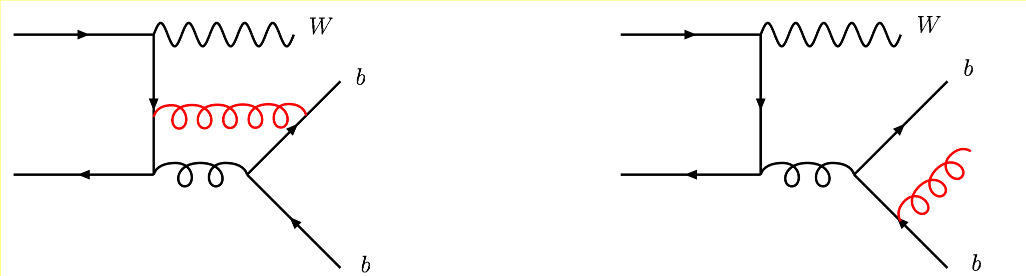




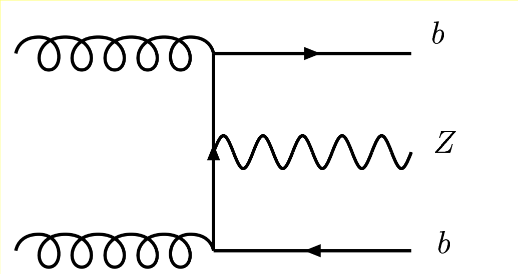
- Overall the cross section decreases by approximately 10% when including the mass. Kinematic distributions are not much affected away from regions of low $p_T(b)$.

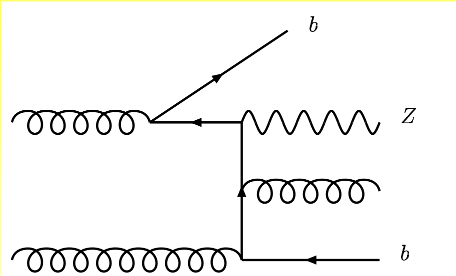
Heavy flavour beyond lowest order

- At NLO, the simple kinematics can be altered:



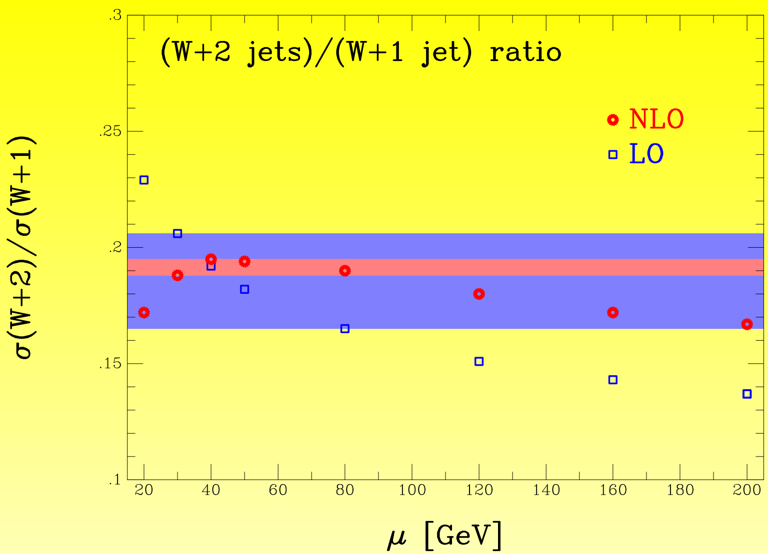
- For heavy flavour production in association with a Z, the b-quarks do not have be produced by gluon splitting. Beyond LO, the difference is further magnified.

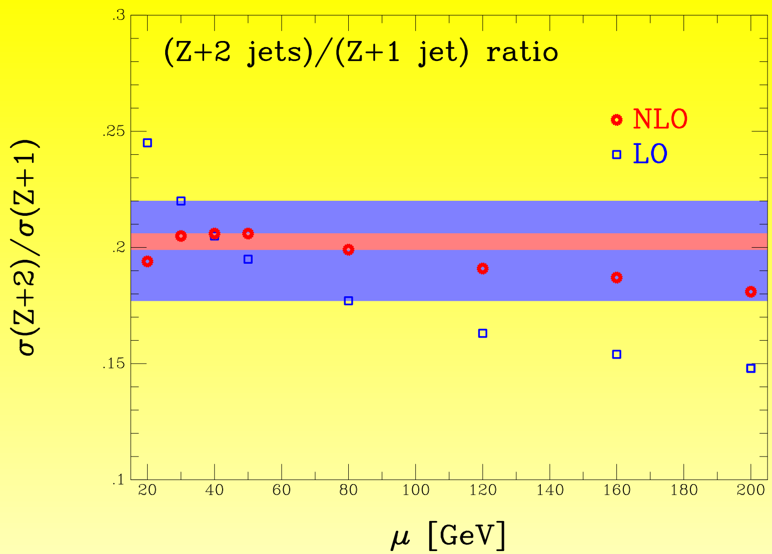




$W/Z+$ jet cross-sections

- The $W/Z+2$ jet cross-section has only recently been calculated at NLO and should provide an interesting test of QCD (cf. many Run I studies using the $W/Z+1$ jet calculation in DYRAD)
- For instance, the theoretical prediction for the number of events containing 2 jets divided by the number containing only 1 is greatly improved.

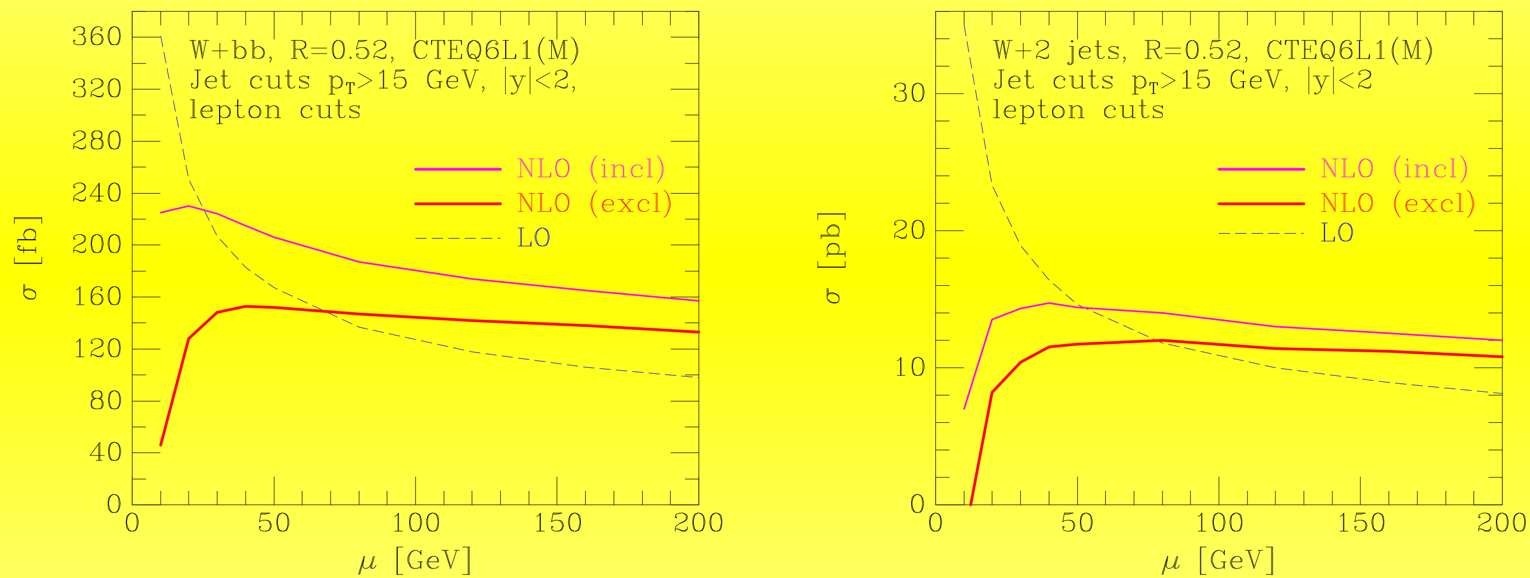




Effect of NLO corrections on $Wb\bar{b}$ and $W + 2$ jet rates

Scale dependence

- Usual scale dependence, much reduced at NLO. Corrections are modest at typical scales, $\mu \sim M_W$.

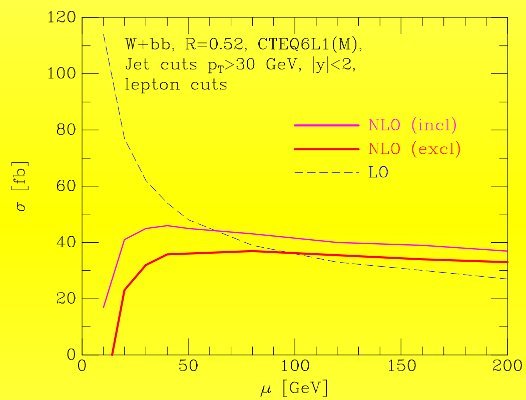


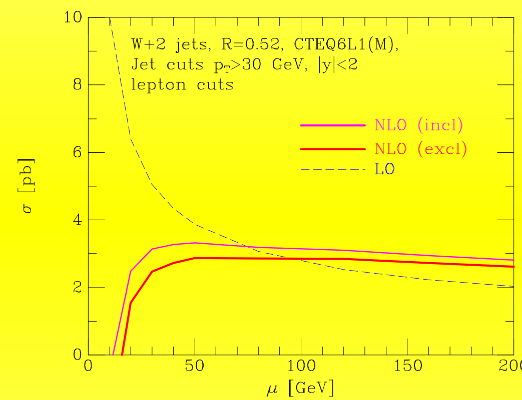
- Exclusive cross-sections stable over a large range of scales.
- Inclusive result (allows $Wb\bar{b}j$, $W+3$ jet configurations) shows more scale dependence, as expected (but still better than LO).

Jet p_T dependence

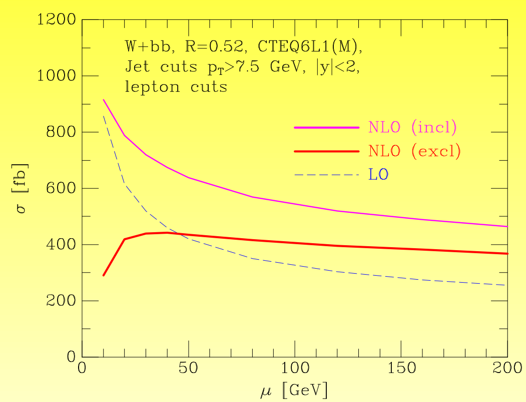
- Increasing the minimum jet p_T reduces the 3 jet contribution compared to the 2 jet one, so the behaviour of the inclusive cross-section improves.

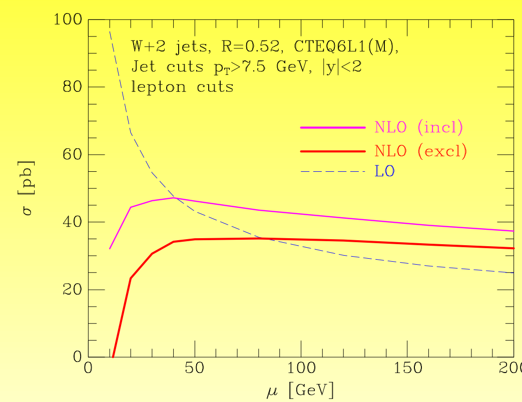
p_T(jet) > 30 GeV





p_T(jet) > 7.5 GeV

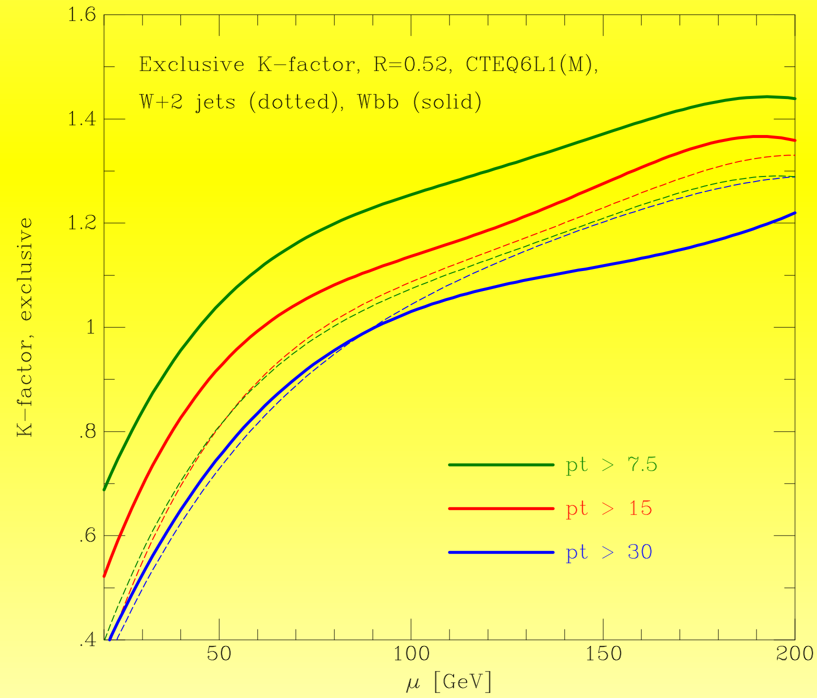




Scale dependence of K-factors

- Strong scale dependence.
- The $Wb\bar{b}$ K-factor varies greatly with the minimum jet p_T, whereas the $W+2$ jets one does not.

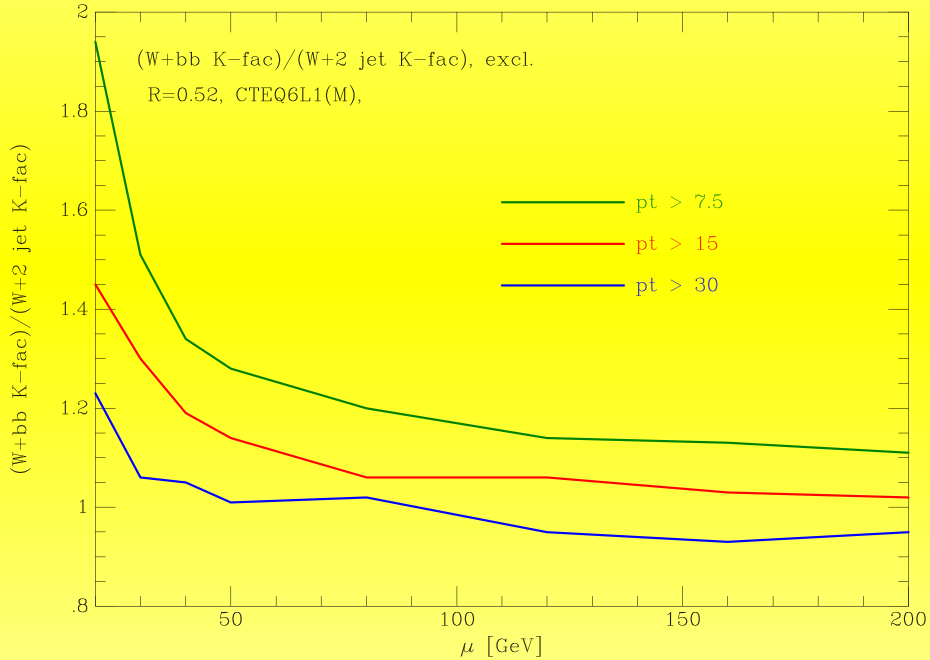
dotted: $W+2$ jets
solid: $W+b\bar{b}$



- Scale dependence has a similar shape for both processes.

K-factor ratio

- Important for CDF's "Method 2". Essentially, is a lowest order estimate of $(Wb\bar{b}/W+2$ jets) reproduced at NLO?

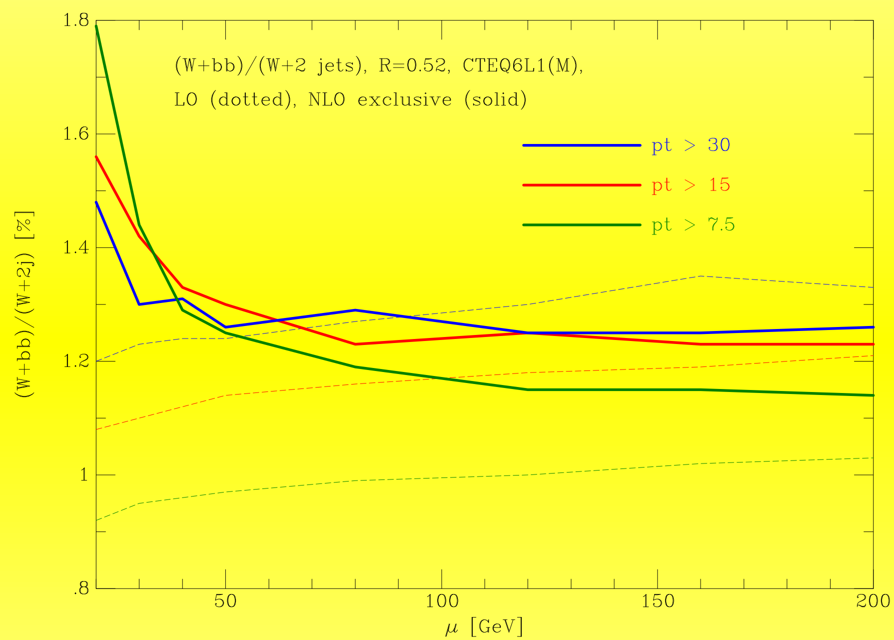


- A qualified "yes" - it is for scale choices around 50 GeV or greater and p_T cuts of about 15 GeV or greater.
- As the jet p_T cut is lowered, the ratio gets worse (increases).

Heavy flavour fraction

- At NLO, this fraction is stable across a wide range of scales.

dotted: LO
solid: NLO exclusive



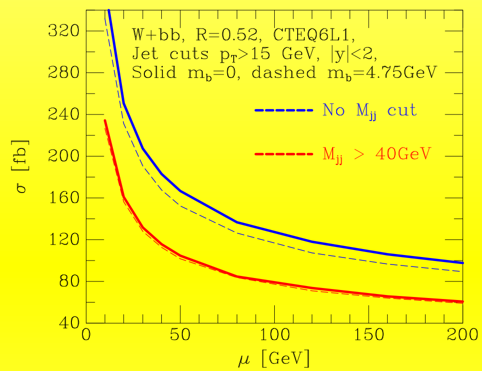
- For a p_T cut of 15 GeV and $\mu \sim M_W$, we have:

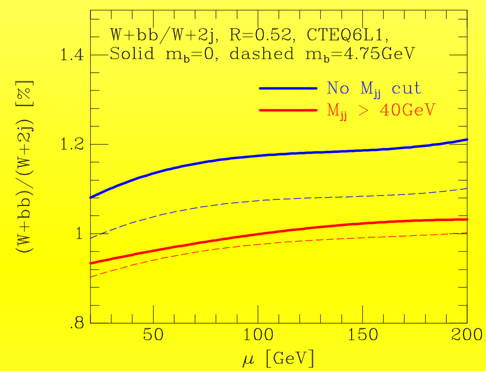
$$\left[\frac{\sigma(Wb\bar{b})}{\sigma(W+2\text{ jets})}\right]_{LO} = 1.16\%, \qquad \left[\frac{\sigma(Wb\bar{b})}{\sigma(W+2\text{ jets})}\right]_{NLO} = 1.23\%$$

Effect of NLO corrections on $Wb\bar{b}$ and $W + 2$ jet distributions

$b\bar{b}$ mass cut

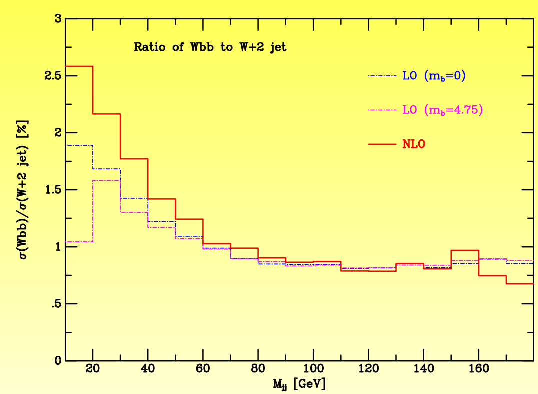
- Such a cut would be helpful, if it could be experimentally enforced:
  - ⋆ It improves the massless approximation





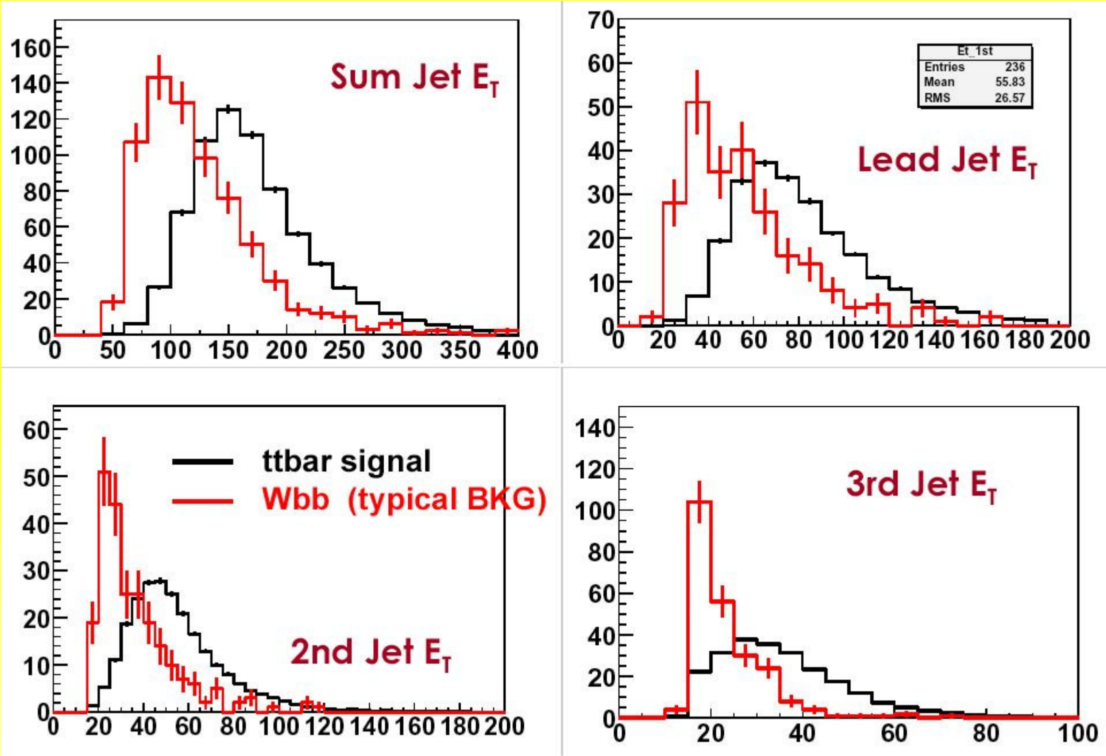
  - ⋆ It reduces this background compared to, for example, $t\bar{t}$ production, since here the b's like to lie at low invariant mass.

LO $(m_b = 0)$
LO $(m_b = 4.75)$
NLO $(m_b = 0)$



Shape comparisons

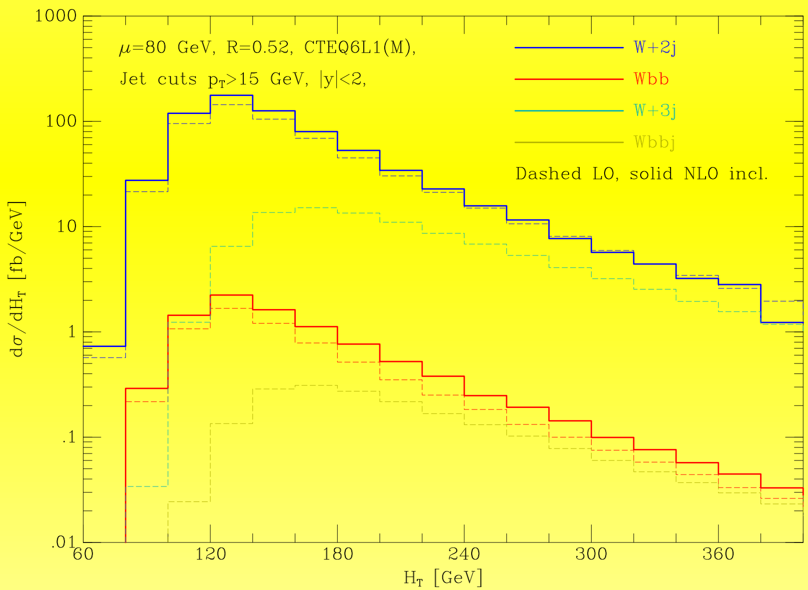
- Shapes of distributions are important in order to either:
  - $\star$ make kinematic cuts to reduce the $W+$ jet backgrounds; or,
  - $\star$ to fit components of signal and background.

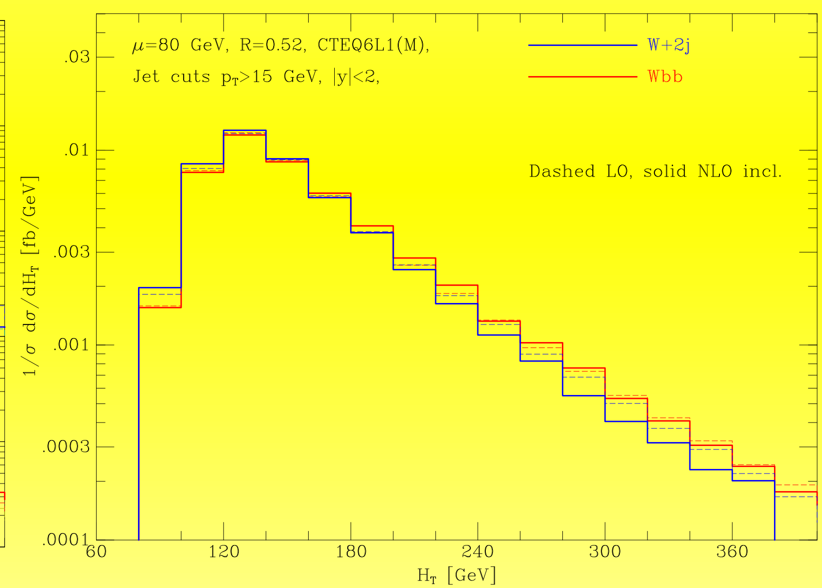


- In particular, are the shapes of relevant distributions similar in the b-tagged and untagged samples? Is this only true at LO?

Kinematic distributions

- NLO behaviour may provide clues to processes with more jets ($\rightarrow$ relevant for $t\bar{t}$), especially for more inclusive variables such as $\sum E_T(\text{jet})$ and $H_T = \sum_{\text{event}} E_T$.





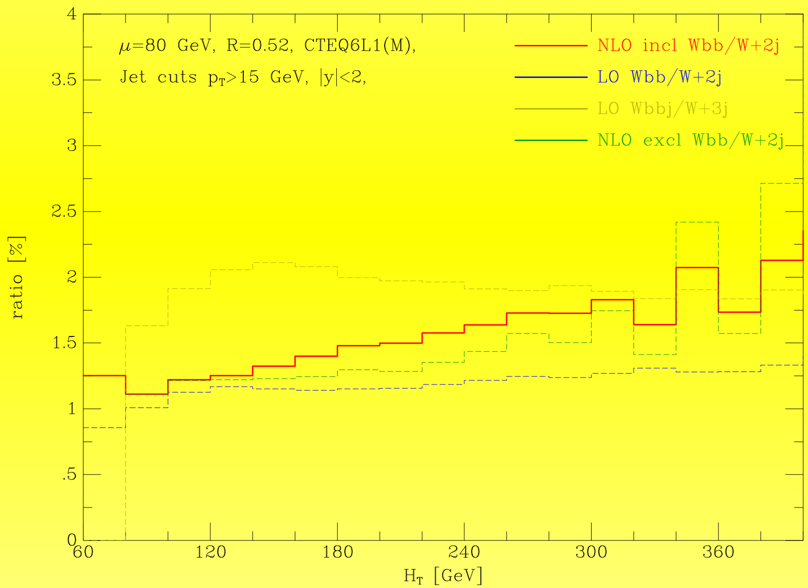
- $Wb\bar{b}$ shape is relatively unchanged at NLO, compared to $W+2$ jets.

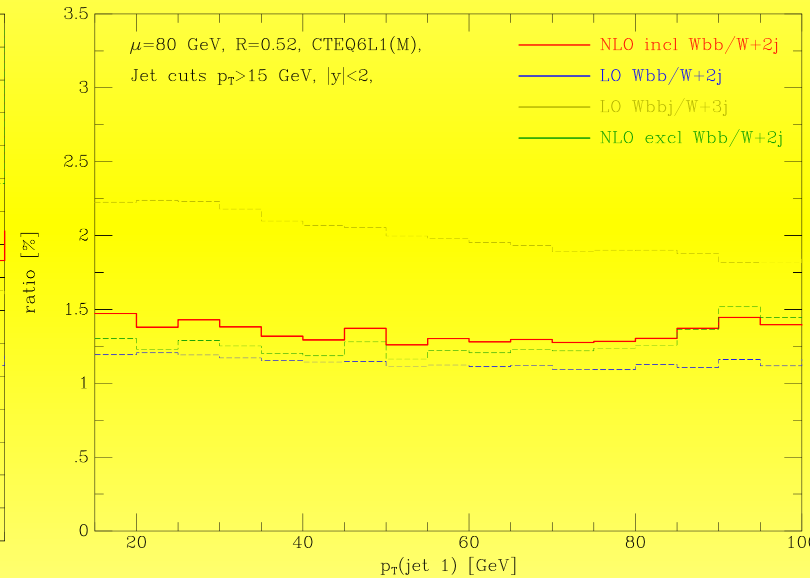
NLO predictions

- At NLO, there is a change of shape in the H_T distribution.

Lowest order
Lowest order+jet

NLO inclusive
NLO exclusive

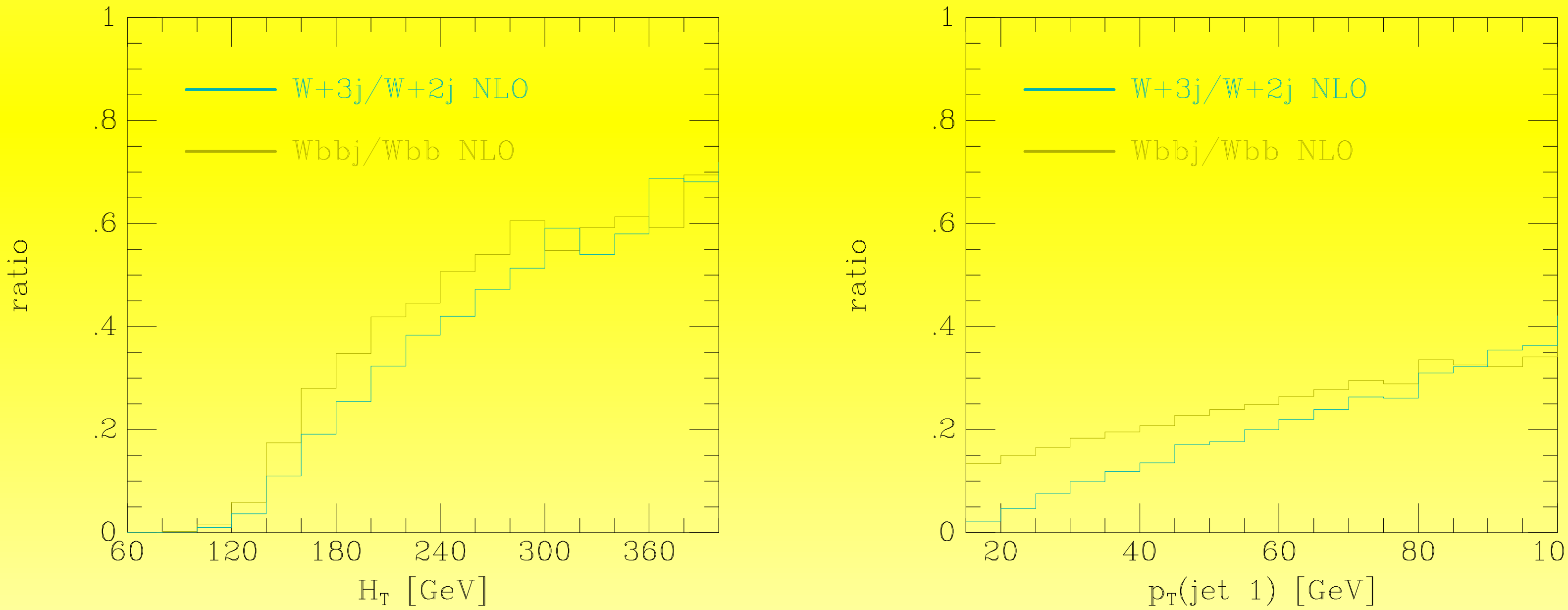




- This change is not entirely due to the extra $W + 3$ jet events allowed in the inclusive sample.
- The p_T distribution of the hardest jet shows no change in shape.

Extra jet contribution

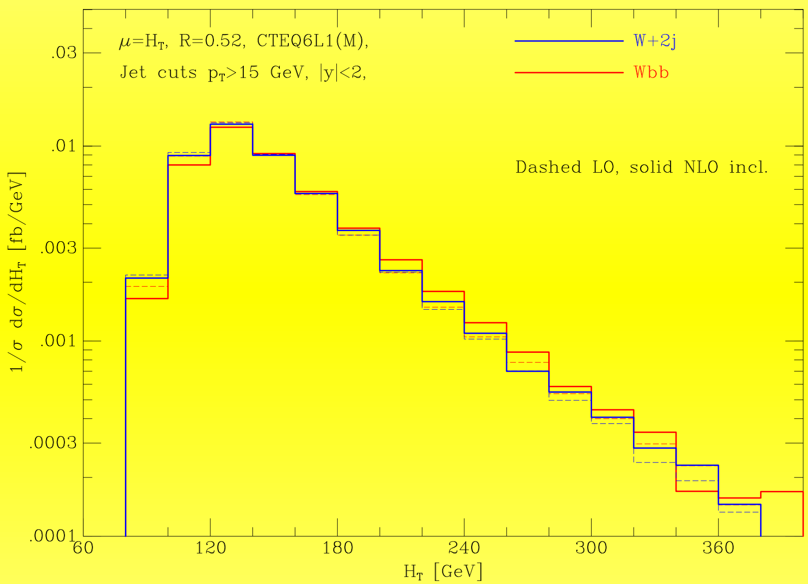
- In the NLO inclusive result, the contribution to the H_T distribution from $W+3$ jet events is negligible at small H_T and dominant at large H_T.
- Similar ratio for $Wb\bar{b}j$ to $Wb\bar{b}$.

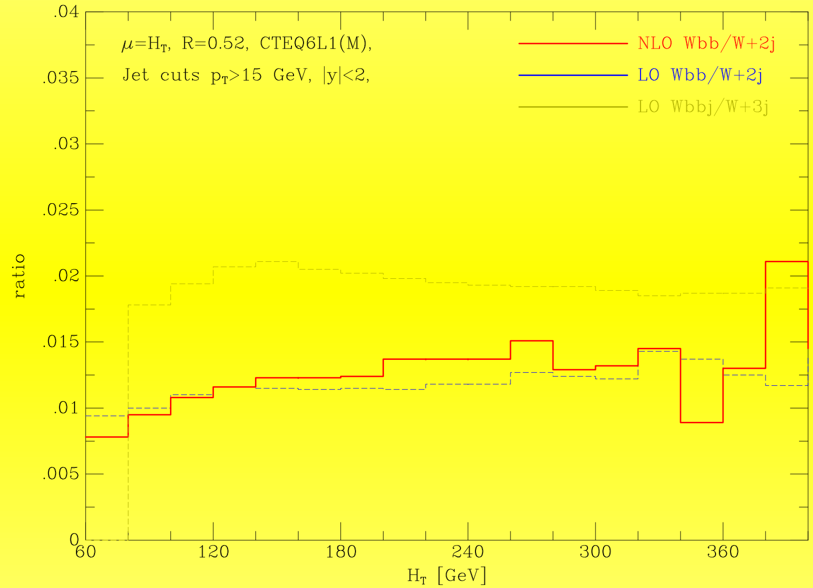


- Extra jet contribution to the jet p_T distribution is never dominant over this range.

Dynamical scale

- This behaviour is somewhat altered if a dynamical scale $\mu = H_T$ is used both at LO and NLO





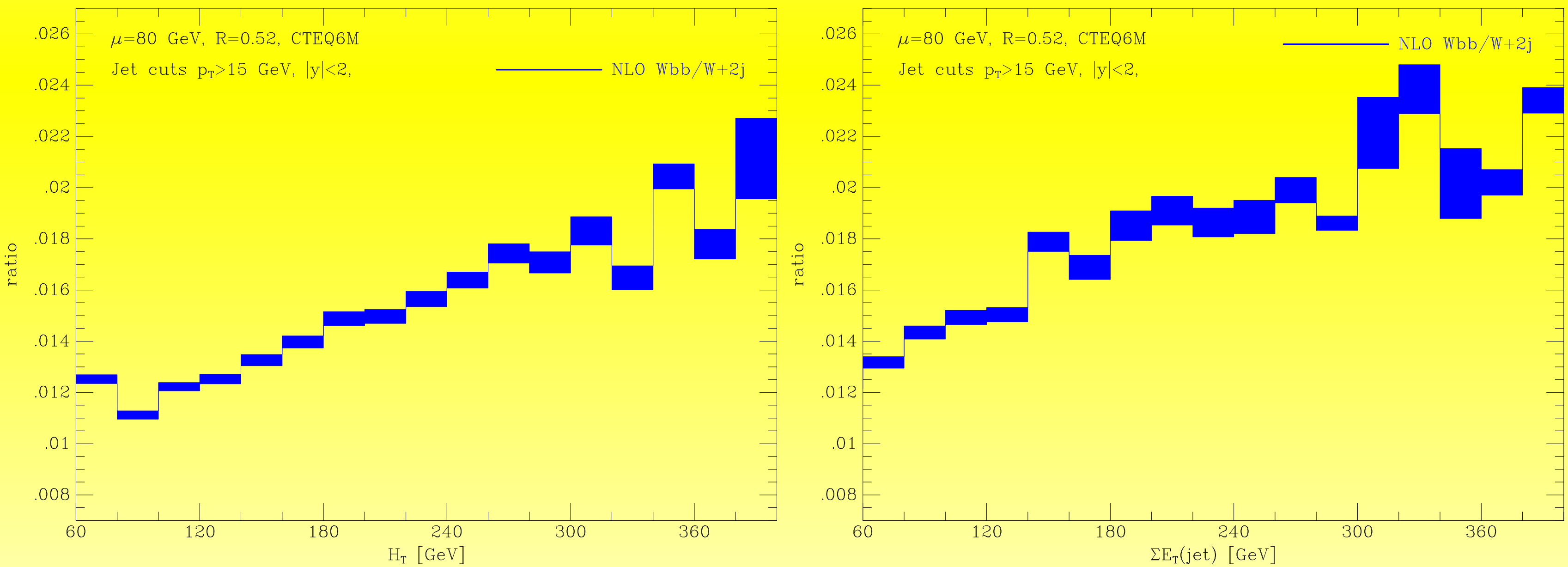
- The shapes of both the $Wb\bar{b}$ and $W+2$ jet distributions change in the same way, leading to a result that is much more encouraging for a LO analysis.

PDF uncertainties

- Total cross-section uncertainty:

$$Wb\bar{b} \to 2.5\% , \qquad W+2j \to 1.5\%.$$

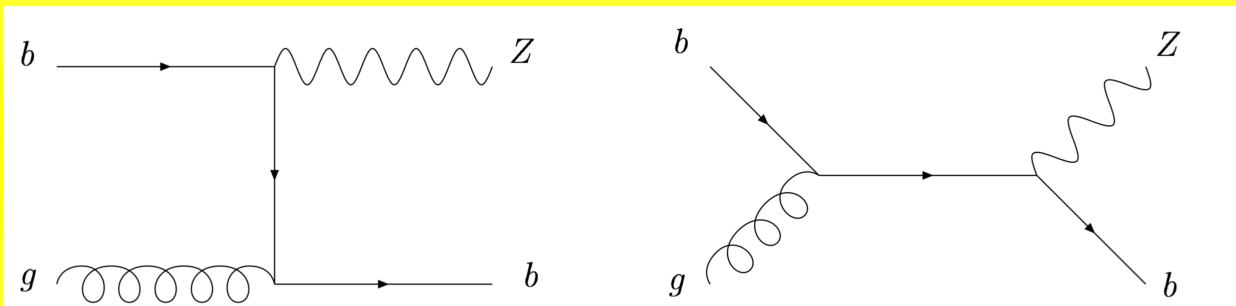
- Uncertainty in the $(Wb\bar{b}/W+2$ jet) ratio:



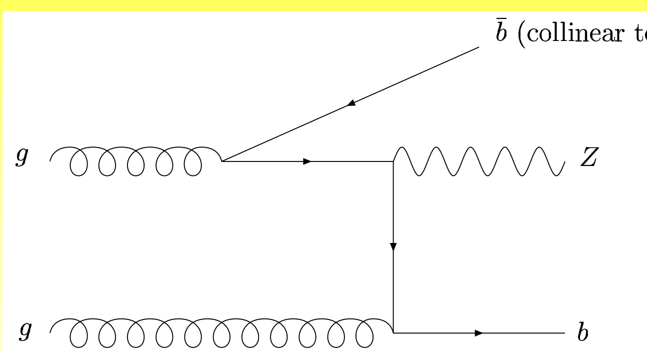
Single-tagged heavy flavour

Heavy flavour fraction revisited

- Often the presence of two b-quarks in the final state is actually only inferred from a single b-tag
- In this case, there is another way of computing the theoretical cross-section. For instance, in the case of $Z+$ heavy flavour:



- Requires knowledge of b-quark pdf's, but compare to:



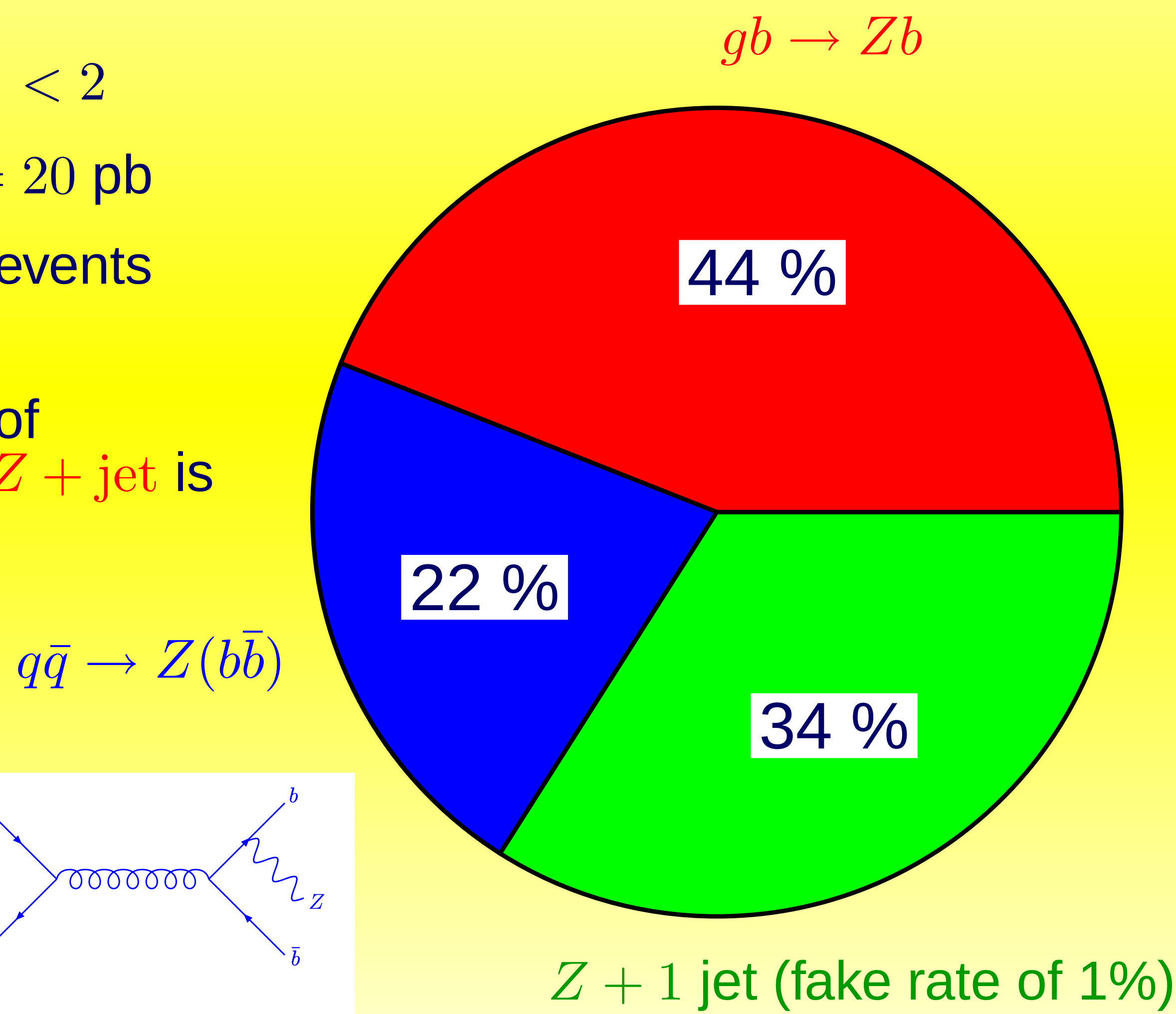
Expansion in $\alpha_s \ln(M_Z/m_b)$ and NLO calculation difficult

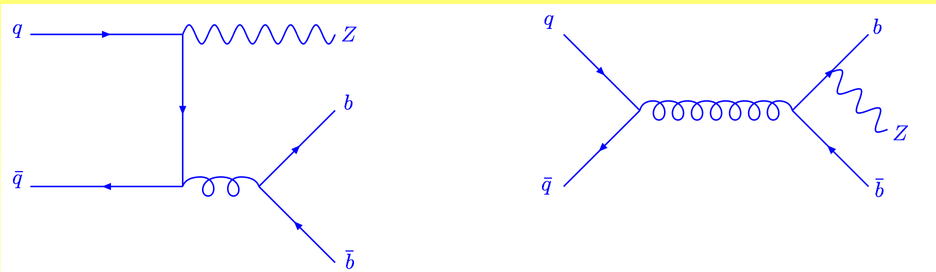
$Z + b$ *at NLO - Run II*

JC, K. Ellis, F. Maltoni and S. Willenbrock, hep-ph/0312024

- $p_T^{\rm jet} > 15$ GeV, $|\eta^{\rm jet}| < 2$
- $\sigma(Z + \text{ one } b \text{ tag}) = 20$ pb
- Fakes from $Z+$ jet events are significant
- Prediction for ratio of $Z + b$ to untagged $Z + \text{jet}$ is

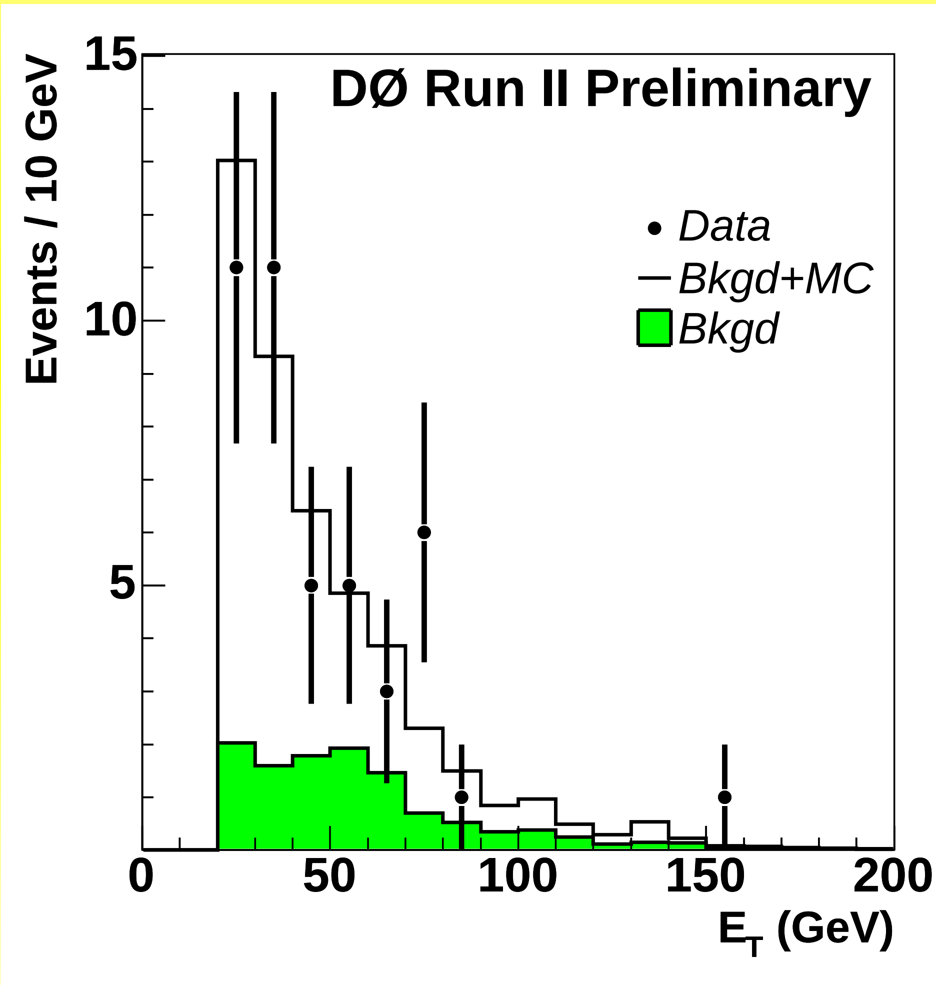
  0.02 ± 0.004





Experimental result

- Based on $189\ \mathrm{pb}^{-1}$ of data from Run II



Preliminary ratio of cross-sections:

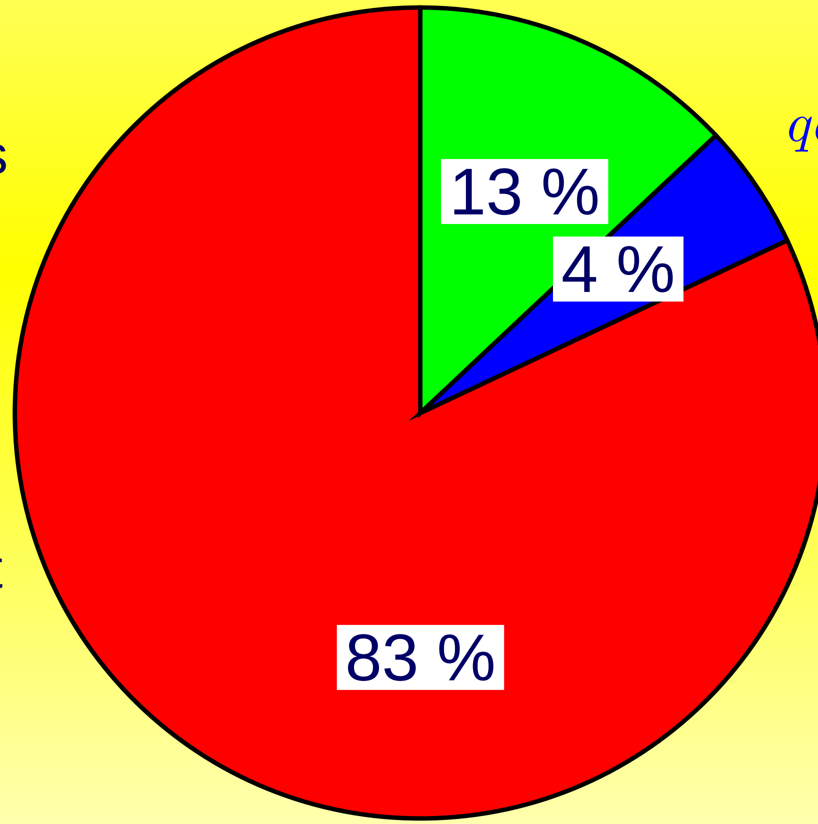
$$\frac{\sigma(Z+b)}{\sigma(Z+j)} = 0.024 \pm 0.07$$

compatible with the NLO prediction

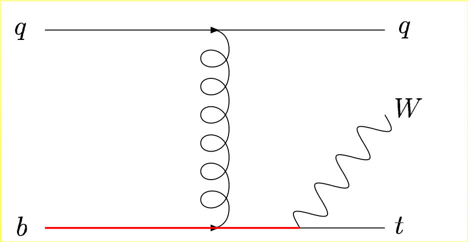
$Z + b$ process in the next version of MCFM will allow a much better comparison with the analysis

LHC expectations

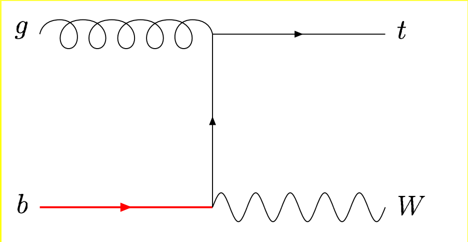
- $p_T^{\mathrm{jet}} > 15$ GeV, $|\eta^{\mathrm{jet}}| < 2.5$
- $\sigma(Z + \text{ one } b \text{ tag}) = 1$ nb
- Fakes from $Z+$ jet events are much less significant and $q\bar{q}$ contribution is tiny
- This should allow a fairly clean measurement of heavy quark PDF's (currently, only derived perturbatively)



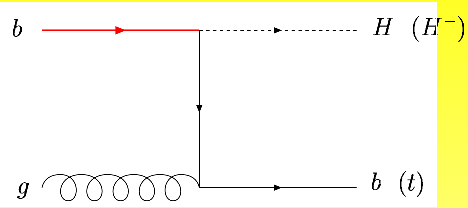
b-PDF uses



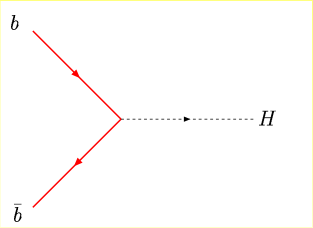
single-top $qb \rightarrow qtW$



single-top $gb \rightarrow tW$



(charged) Higgs+b



inclusive Higgs

Calculational directions

- $W + 3{,}4$ jet cross-sections at NLO
  - ⋆ New technology needed: probably not ready for Run II

Nagy and Soper, hep-ph/0308127
Giele and Glover, hep-ph/0402152

- Inclusion of b mass effects in $Wb\bar{b}$ and $Zb\bar{b}$
  - ⋆ Technology available: some efforts are underway . . . c.f. $Hb\bar{b}$

W. Beenakker et al., hep-ph/0211352
S. Dawson et al., hep-ph/0311216

- Merging of existing NLO calculations with a parton shower
  - ⋆ Possible: MC@NLO has yet to be applied to $W/Z+$ jets
- Further study of recent ideas regarding parton showers (most promising in the short term)
  - ⋆ Matrix elements corrections - CKKW, . . .
  - ⋆ How much of the effects of NLO are taken into account by combining matrix element calculations with parton showers?

F. Krauss et al.

Outlook

- The $W+$ jets channel (including heavy quarks) is very important for many studies in Run II.
- Unfortunately, for events with many jets we are limited to LO predictions for rates and distributions.
- However, there should be lots to learn from the NLO corrections that we know about. The highest multiplicity that is currently available is production of $Wb\bar{b}$ and $W+2$ jets.
- Implications for Run II analyses.
  - ⋆ Results suggest that some relevant observables do not suffer from large NLO effects and we can proceed with more confidence in analyses based on LO tools.
  - ⋆ However, beware of variables that change shape at NLO (H_T).
  - ⋆ These statements are heavily dependent on scale choices.
- Further comparisons with parton shower approaches and data is the way forward.